LA-UR -86-3050

CONF-860919--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--86-3050

DE87 000134

TITLE: NEW DEVELOPMENTS IN OPTICAL PHASE CONJUGATION

AUTHOR(S): Irving J. Bigio
Robert A. Fisher
Timothy R. Gosnell
Norman A. Kurnit
Thomas R. Loree
Thomas R. Moore
Andrew V. Nowak
David E. Watkins

SUBMITTED TO: PROCEEDINGS OF THE 6TH INTERNATIONAL SYMPOSIUM ON GAS FLOW AND CHEMICAL LASERS, September 8 - 12, 1986, Jerusalem, Israel

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New Developments in Optical Phase Conjugation

I.J. Bigio, R.A. Fisher, T.R. Gosnell, N.A. Kurnit, T.R. Loree, T.R.. Moore, A.V. Nowak, and D.E. Watkins

Los Alamos National Laboratory
Los Alamos, New Mexico 87545
USA

Introduction

Optical phase conjugation has ceased to be regarded as merely a scientifically intertesting laboratory phenomenon. It is now being invoked as a tool to deal with various laser problems that do not yield easily to more conventional solutions. Thus, in addition to the continuing research on the fundamental mechanisms in various methods of phase conjugation, activities at the Los Alamos National Laboratory have also addressed development issues of more practical relevance. For a tutorial introduction to the concepts of optical phase conjugation we direct the reader to references [1] and [2], whereas more details on various subtopics can also be found in [2].

In this review two major areas of investigation in optical phase conjugation are discussed: stimulated Brillouion scattering and dynamic effects in photorefractive media.

I. Recent Results in Stimulated Brillouin Scattering

In this section we discuss the issue of whether or not a common phase can be impressed on the reflection of multiple beams through the process of stimulated Brillouin scattering (SBS). Such a scheme could be of great value to applications requiring phased arrays of lasers, which are individually limited in size, so as to produce a coherent set of laser beams equivalent to what would be produced by a much larger single laser. We demonstrate that this can be accomplished for a pair of pump beams derived from the same laser, either through the use of a common focus or by seeding. We also discuss the effect of seeding on the fidelity of the phase conjugation.

Seeding SBS using a broadband pump beam:

If the bandwidth of a pump laser is broader than the frequency shift that results from Brillouin scattering, then light from the pump laser can be used to seed the Brillouin scattering. This is accomplished by injecting a small fraction of the pump laser energy in the backwards direction. Here we concern ourselves with the effect of this seeding on the amplitude of the reflected wave. The effect on the phase is considered below. The effect of seeding on the reflectivity is shown in Fig. 1. This experiment was carried out with a XeCl laser running with an effective bandwidth (in each of two lines) of ~0.1 nm. As can be seen in the figure, when the intensity of the pump beam is slightly below threshold, adding the seed initiates the SBS process, thus lowering the effective threshold. The seed also affects the reflectivity over the pump energy range (for these experimental conditions) of ~1.5 - 5 mJ. At higher pump energies, the influence of the seed on reflection amplitude is minimal.

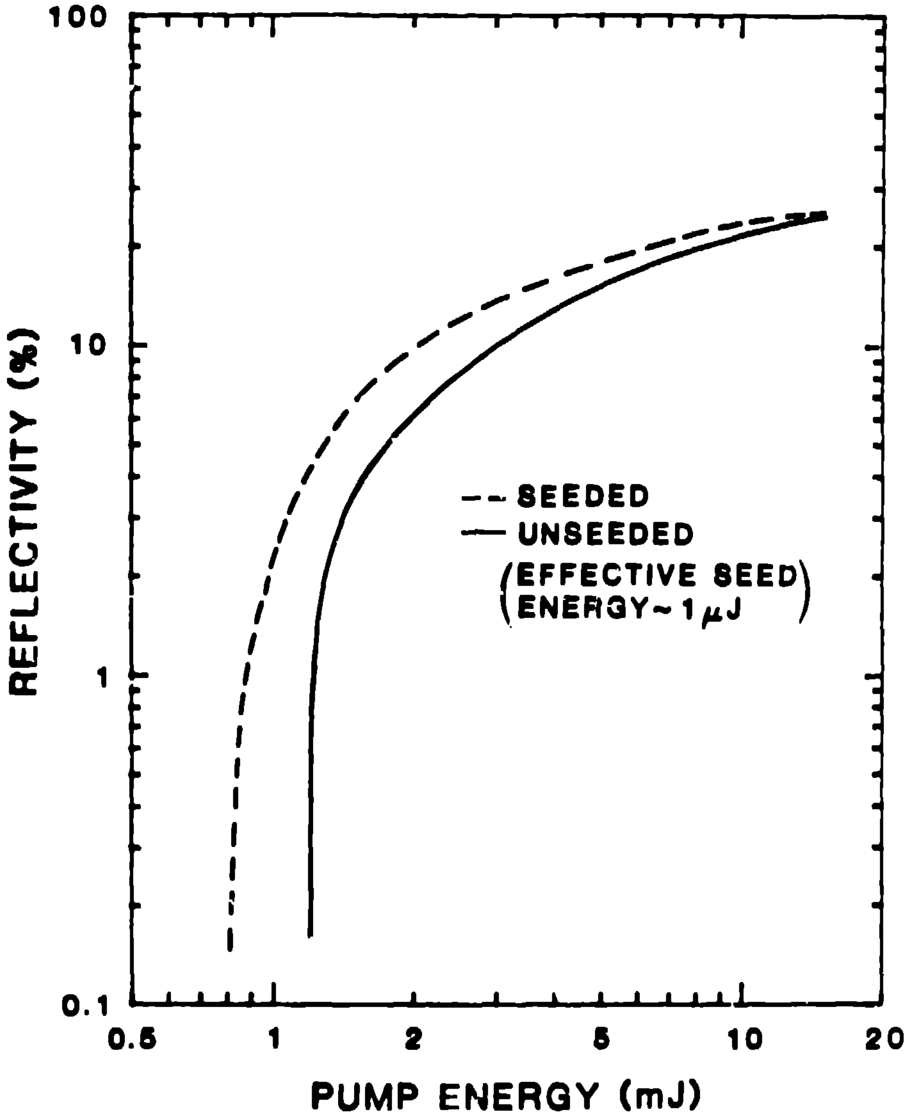

Fig.1. The SBS reflectivity for a wide range of pump energies and a constant seed

<u>Phase-locking of two SBS beams:</u>

We began our investigation of phase locking by applying a quantitative diagnostic to a two-beam common-focus geometry [3] as shown in Fig. 2. Two 355-nm pump beams of equal intensity (derived from a frequency-tripled YAG laser) are generated by slightly misaligning a Michelson interferometer. This generates a fringe pattern which can be observed both before and after reflection from an SBS cell. By varying the misalignment of the Michelson, the focal volumes within the SBS cell (see Fig. 2) can be separated or made to overlap. In addition, one can inject a backwards-propagating seed beam into the cell through the rear window. The locking of the fringes is observed by placing photodiode detectors behind small pinholes which view only a fraction of a fringe in both the reference and the SBS fringe patterns. The degree of correlation between the signals is a measure of the phase locking.

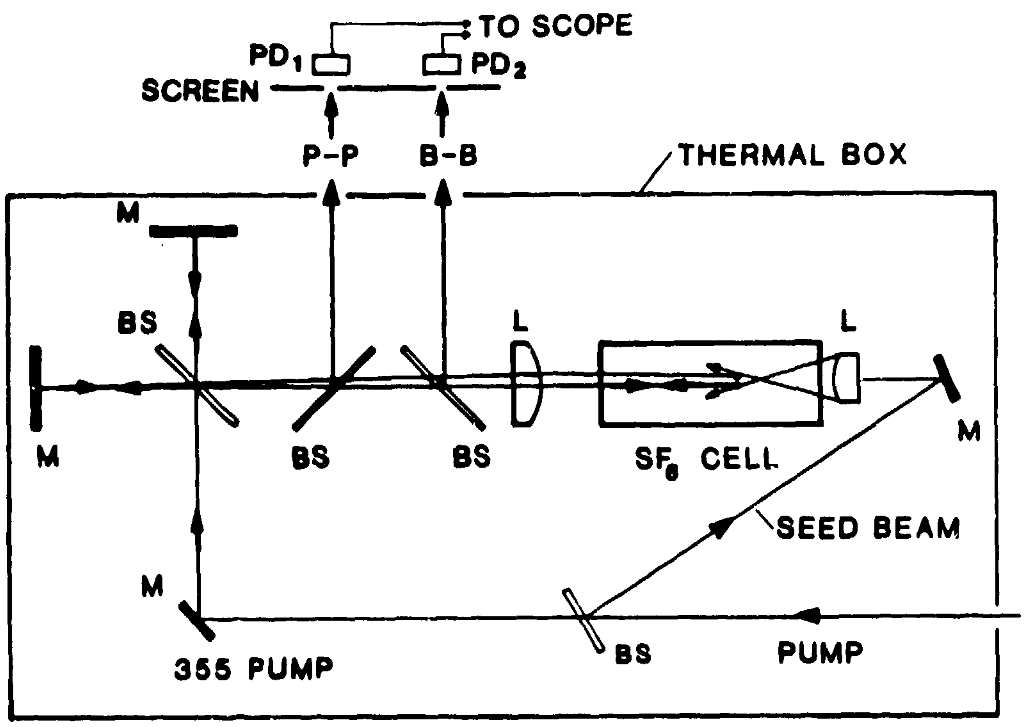

Fig 2. Experimental layout for phase-locking of two beams. The left end is the Michelson interferometer. The pump beam reference fringe pattern is labeled p-p, and the pattern from the Brillouin cell is labeled B-B

Figures 3 and 4 show the experimental results for overlapped and separated focal spots without seeding. In Fig. 3, where the 50 µm spots were separated by only 25 µm, a high degree of correlation is observed. In Fig. 4 the separation is 65 µm, and the plot appears random. Intermediate separations of the focal spots give intermediate degrees of correlation in the scatter plots, up to a separation of about 60 µm, where the unlocking appears to be complete. Figure 5 shows the affect of adding a seed beam (of relatively large diameter) when the focal spots are separated by 100 µm. The seed introduces a background component to the pattern from the Brillouin cell, so the data no longer intersects the origin. The pattern, however, exhibits much higher correlation than when unseeded.

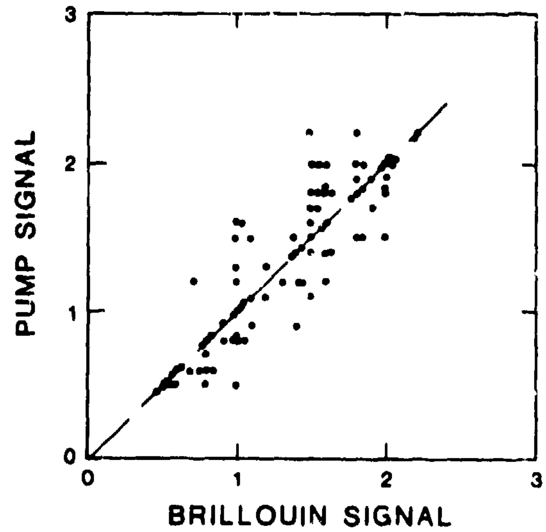

Fig.3. Scatter plot of the photodiode signals showing phase locking for overlapped focal spots. No seed was present, and the separation of the two 50-um spots was 25 um

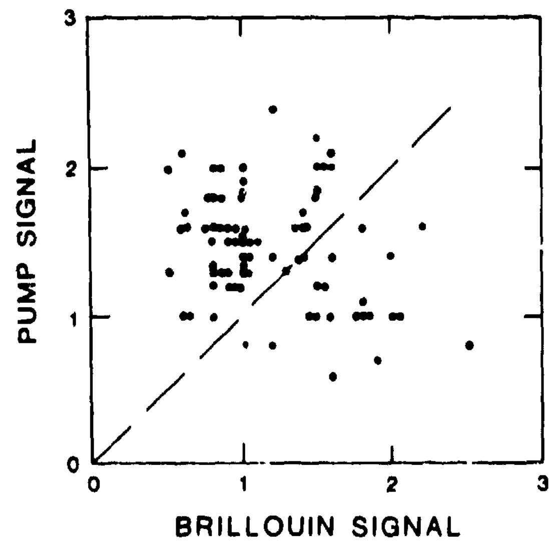

Fig.4. Scatter plot with the focal spots separated by 65 um and no seed present

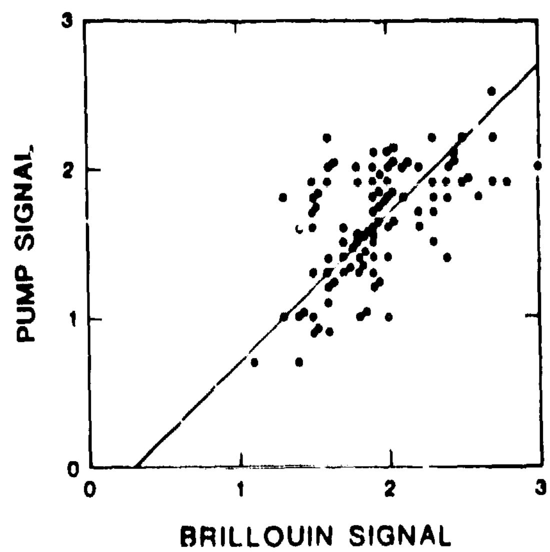

Fig.5. Scatter plot with the foci separated by 100 um and the seed beam present. The data not longer intersect the origin because of the background light of the seed.

The effect of seeding on phase conjugate fidelity

We discussed above the effect of seeding on the relative phases of two beams in SBS. We have also investigated the effect of seeding on the phase-conjugate fidelity of SBS using the experiment diagramed in Fig. 6. In this experiment the near and far field intensities are observed by examining patterns from a double slit as a diagnostic for the fidelity of phase conjugation. The results are shown in Fig. 7. In the unseeded case, the near field pattern of the SBS beam loses some of the high spatial frequency components of the input pump beam, but retains the low frequency spatial structure. In the far field, the two interference patterns are nearly identical. In the seeded case, the near field again shows a loss of high spatial frequency components, but retains the basic structure. However, in the far field, the interference pattern from the seeded SBS cell does not show the same structure as the input pump beam interference pattern, and it is evident that seeding has reduced the fidelity of the phase conjugation process.

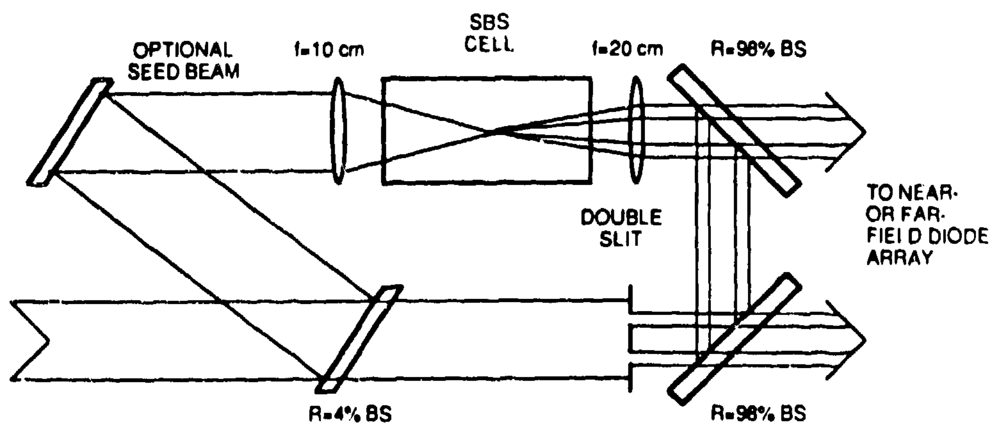

Fig.6. Layout of the experiment used to examine the phase conjugate fidelity of seeded SBS

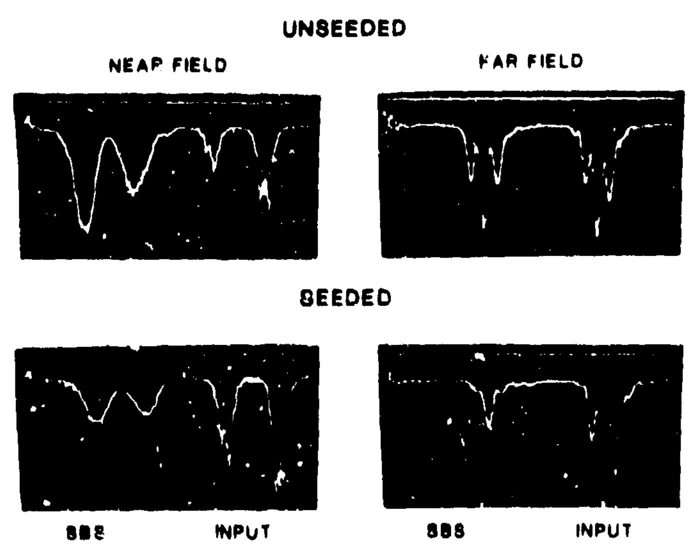

Fig 7. Near- and far-field intensity profiles of the pump beam and the SBS phase conjugate beam for seeded and unseeded SBS

Another important beam characteristic relevant to fidelity of phase conjugation is the spatial coherence. Using a simple interferometer which superimposes a phase-conjugate wave (derived from an initially fully spatially coherent pump wave) with its mirror image about a vertical plane, a measure of the beam's spatial coherence is indicated by the fraction of the full beam diameter in the horizontal plane occupied by interference fringes. Preliminary qualitative results obtained with this technique show some surprising trends: while the spatial coherence of the conjugate beam decreases with increasing f-number of the pump beam, the coherence decreases with increasing intensity at a fixed f-number. The latter observation indicates that at high pump intensities phase locking across the transverse direction is apparently lost. On the other hand, if increased pump intensity in the focal volume is achieved by reducing the pump-beam f-number, the former observation leads to the opposite conclusion. Evidently, spatial coherence of the phase-conjugate wave is determined not only by the transverse characteristics of the optical and acoustic fields within the focal volume, but also by the longitudinal fiels characteristics. Further, just as amplitude and longitudinal phase control can be obtained with a seed beam, one might also expect to observe seed-induced transverse phase control. Experiments of this type should yield greater understanding of the mechanisms for loss of beam fidelity following phase-conjugate reflection by stimulated Brillouin scattering.

Other SBS studies

In addition to the work described above in detail, studies have also been carried out in the use of SBS for pulse compression and for beam cleanup in small oscillator/amplifier systems. Pulse compression to ≤ 1ns was accomplished by sending a backward seed through a long SBS cell to extract energy from the pump beam [4].

II. Internal Beam Patterns in Barium Titanate Phase Conjugators

In the last few years a large amount of attention has been paid to photorefractive optical phase conjugators [5]. Although most non-linear optical effects require megawatts of laser intensity to be detected (e.g., stimulated Brillouin scattering, Kerr-like degenerate four-wave mixing, etc.) photorefractive phenomena can manifest themselves at intensities of only a few watts/cm^2. In general, for weaker optical intensities the response time of the photorefractive medium merely becomes longer. Among photorefractive media, single-crystal $BaTiO_3$ has been the subject of great interest because of its ability to produce "self-pumped" phase conjugate reflections [5]. The usual external counterpropagating pump beams are not needed.

Consider a nearly cubic sample of $BaTiO_3$, about 5 mm on a side, such as the one shown in Figs. 8 and 9. It is being pumped by a CW beam from an argon-ion laser. Under appropriate conditions of light polarization and beam-crystal geometry, a portion of the incident wave will typically fan away from the main path in the direction of the c-axis, towards a corner of the crystal. This effect readily observable in Fig. 8. A phase-conjugate reflection results when this auxiliary beam reflects off the corner and crosses the main beam to provide the requisite counterpropagating pumpwaves.

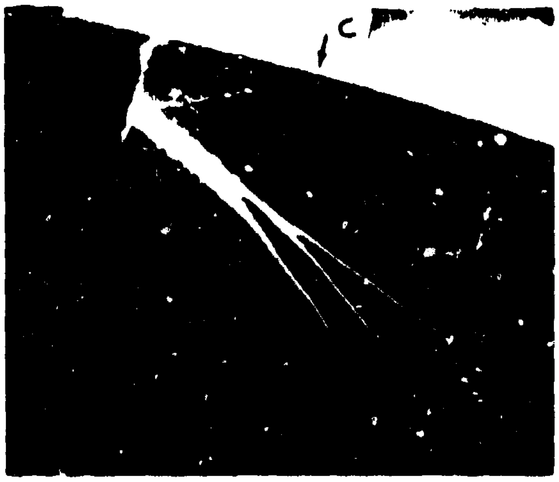

Fig.8. Top view of $BaTiO_3$ crystal showing the basic auxiliary beam pattern for "self-pumped" phase conjugation. The laser beam entered from the top of the figure. The arrow marks the c-axis

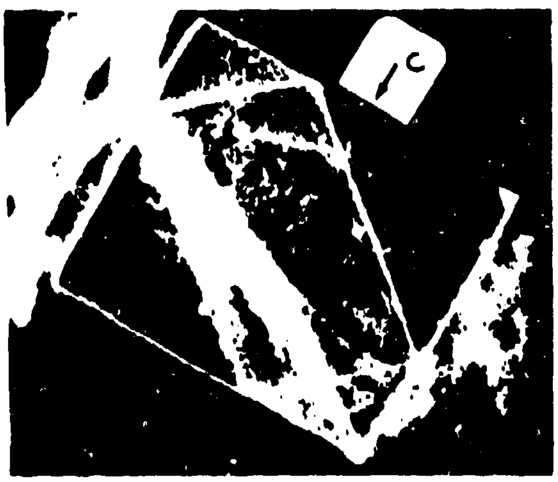

Fig.9. The TIR ring in $BaTiO_3$. The beam entered from the top of the figure. The arrow marks the c-axis

The experimental apparatus used for this study is shown in Fig. 10. The cw argon-ion laser was prism-tuned to the 514.5-nm line and was operated in a single longitudinal mode. The Faraday isolator served to decouple the experiment from the laser. After passage through the beamsplitter, the beam was focused by a 30-cm lens into the sample. The beam power and beam diameter were approximately 75 mW and 50 μm, respectively, resulting in an intensity of the order of 4 kW/cm^2. The beam polarization and the crystal c-axis were always oriented in the horizontal plane.

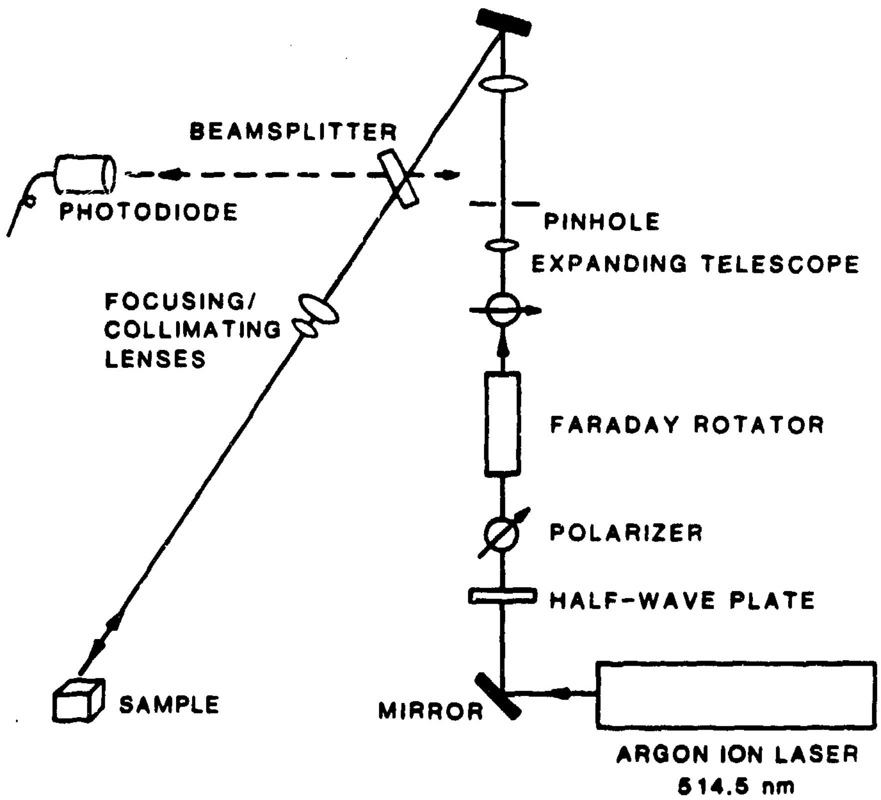

Fig.10. Experimental apparatus for the study of phase conjugation and internal beam patterns in photorefractive $BaTiO_3$

The photographs in Figs.8 and 9 show a top view of the crystal with the laser beam entering from the upper edge of the figure. The direction of the c-axis is indicated by the arrow. Patterns were recorded either with a still camera or a video recorder. The video format allowed, upon replay, a detailed examination of the changing beam patterns within the crystal.

In Fig. 9 one can see the total internal reflection (TIR) ring, a curious discovery which was first observed in our laboratory. It was most easily obtained using a beam which was half obscured by a vertical knife edge prior to being focused by the 30-cm lens. The ring was first seen while studying the pattern of Fig. 8. The ring appeared with no external prompting and was accompanied by a drop in the phase conjugate signal. Most often the ring would continue to evolve, changing its shape, becoming sharper or more diffuse, brighter or dimmer. It would eventually disappear just as unexpectedly as it appeared. An interferometric check indicated that the frequency of the phase conjugate light was unchanged both before and after formation of the ring. The direction of light circulation within the ring was determined by extracting some of the light into a second $BaTiO_3$ crystal. The light was found to propagate primarily in the counterclockwise direction although on a few occasions both directions were observed. We believe that the ring within the crystal may be the result of two-beam coupling between the main beam and scattered light which finds a closed loop via internal reflections around the crystal. This would explain the drop in phase conjugate reflectivity when the ring is formed.

Another curious effect was the erasure of the auxiliary beam pattern and deletion of the phase-conjugate signal when the transmitted beam was reflected back into the crystal along the **right** side of the incident beam. When, however, the beam was returned along the **left** side of the incident beam no major changes in either the auxiliary beam pattern or the phase-conjugate signal occurred. We also observed, for certain configurations, that when the crystal was translated at right angles to the incident beam, the auxiliary beam pattern moved with the crystal, appearing to detach itself from the incident beam.

Amplitude oscillations were often observed in the $BaTiO_3$ phase-conjugate signal. These appeared to be chaotic although in some cases they showed very nearly periodic behavior with periods between 0.01 and 5 seconds.

A full explanation of these effects remains to be determined.

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